

# “INVESTIGATION OF MECHANICAL PROPERTIES OF CONCRETE BY PARTIAL REPLACEMENT OF METAKAOLIN BY CEMENT AND COPPER SLAG BY FINE AGGREGATE USING POLYPROPYLENE FIBERS”

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**Abstract** - This experimental work examines the performance of M30 grade concrete produced by partially replacing cement with metakaolin and fine aggregate with copper slag, along with the addition of polypropylene fibres. Basic material tests confirmed the suitability of the constituents: the specific gravity of cement was 3.12, fine aggregate 2.46, coarse aggregate 2.73, metakaolin 2.40, and copper slag 3.74. The fineness of cement was measured as 6 percent, while the standard consistency was found to be 32 percent. Water absorption values were 0.1 percent for fine aggregate and 0.5 percent for coarse aggregate, all within permissible limits. Concrete mixes were prepared with a water-cement ratio of 0.40, cementitious content of 394 kg/m<sup>3</sup>, fine aggregate 791 kg/m<sup>3</sup>, coarse aggregate 1068 kg/m<sup>3</sup>, and admixture content of 1.1 percent by weight of cement. Various mix design was done by partially replacing with copper slag as fine aggregate by a percentage of 40,50,60,70 percent with constant replacement of 10% metakaolin as cement and additionally using polypropylene fibres of 0.8%. Compressive strength and split tensile strength was determined at curing periods of 28 days. Results indicated steady strength development with age, and the optimum mix incorporating metakaolin, copper slag, and polypropylene fibres was also added to the mix achieved a 28-day compressive strength of 35.33 MPa compared to the control mix average of 29.83 MPa and the split tensile strength varied from 2.78(control mix) to 3.2 MPa (50% copper slag, 10% metakaolin, 0.8% polypropylene fibres). The study concludes that the combined use of metakaolin, copper slag, and polypropylene fibres improves compressive strength and split tensile strength and provides a sustainable alternative to conventional concrete mixtures.

## 1. INTRODUCTION

Concrete is the most widely used material in the construction industry due to its strength, versatility, and adaptability. However, the production of cement, its key

binding component, generates a large amount of carbon dioxide, contributing significantly to environmental pollution. To overcome this issue, researchers have explored the use of supplementary cementitious materials and industrial by-products to partially replace cement and natural aggregates, thereby improving performance and promoting sustainability.

Metakaolin, obtained through calcination of kaolinitic clay, is a highly reactive pozzolanic material that enhances the compressive strength, durability, and chemical resistance of concrete. It reduces porosity, shrinkage, and permeability, while promoting the formation of additional calcium silicate hydrate. Copper slag, a by-product of the copper smelting industry, provides another sustainable alternative by replacing natural sand. With its high specific gravity and angular particles, copper slag improves density, workability, and strength, while simultaneously addressing waste disposal problems. In addition, polypropylene fibres are widely used to reduce plastic shrinkage cracks, improve toughness, and enhance durability. Even in small dosages, they significantly improve the crack resistance of concrete.

In this study, M30 grade concrete was prepared by replacing cement with 10 percent metakaolin, fine aggregate with copper slag at 40, 50, 60, and 70 percent, and by incorporating 0.8 percent polypropylene fibres. Basic material tests such as specific gravity, fineness, water absorption, and consistency were performed to ensure the quality of the ingredients. Concrete cubes were then cast and tested for compressive strength at 28 days to evaluate the effect of these modifications on strength development.

The aim of this work is to develop and evaluate a sustainable concrete mix by partially replacing cement with metakaolin and sand with copper slag, along with the addition of polypropylene fibres, in order to enhance compressive strength and improve the overall performance of M30 grade concrete

## 2. LITERATURE REVIEW

**Itikela Durga Saikiran et al. (2021)** carried out an investigation on high-strength concrete using metakaolin, alccofine, and copper slag as partial substitutes for cement and fine aggregate. Their work concluded that the combination of 15% metakaolin, 10% alccofine, and 60% copper slag produced the most favorable results in terms of mechanical strength and workability.

**Balgourinijad et al. (2022)** studied lightweight concrete incorporating polypropylene fibres and metakaolin when exposed to high temperatures ranging from 200°C to 600°C. The results revealed that 0.8% polypropylene fibres with 10% metakaolin provided better crack resistance, reduced water absorption, and improved impact energy absorption, making the mix more durable under thermal conditions.

**Vijayaprabha Chakrawarthy et al. (2021)** examined concrete reinforced with polypropylene fibres and partially replaced fine aggregate with copper slag. Their research highlighted that a 40% replacement of sand with copper slag and the addition of 0.6% polypropylene fibres significantly enhanced impact resistance and energy absorption capacity compared to conventional concrete.

**Naveen Kundargi et al. (2023)** explored the performance of self-curing concrete prepared with metakaolin, copper slag, and polyethylene glycol (PEG-400). Their findings indicated that replacing cement with 10–20% metakaolin and sand with 40–60% copper slag improved compressive and tensile strength, showing the potential of integrating self-curing agents with mineral admixtures.

**Shaik Fazlur et al. (2019)** investigated concrete with partial replacement of cement by metakaolin and coarse aggregate by blast furnace slag. The study showed that the addition of 10% metakaolin and gradual substitution of coarse aggregate enhanced compressive and tensile strength, demonstrating the usefulness of industrial by-products in concrete.

**Shakil Khan et al. (2021)** worked on M30 grade concrete by introducing metakaolin and polypropylene fibres, while natural sand was replaced with Robo sand at varying levels. Their results indicated that mixes with 10% metakaolin and 40–50% Robo sand delivered superior strength performance compared with the control mix.

**Prasad et al. (2021)** analyzed concrete mixes incorporating metakaolin, glass powder, and silica fume as cement replacements. For M40 grade concrete, the results showed notable improvements in compressive, tensile, and flexural strength, particularly at 28 days of curing, compared with conventional mixes.

**Sina et al. (2017)** investigated self-compacting concrete made with metakaolin, ground granulated blast furnace slag,

and fly ash. They found that 20% metakaolin replacement improved early-age strength, workability, and microstructure due to enhanced pozzolanic activity and better formation of C–S–H gel in the cement matrix.

## 3. EXPERIMENTAL PROGRAM

This investigation was designed to evaluate the performance of M30 grade concrete by incorporating metakaolin, copper slag, and polypropylene fibres. The program involved material testing, mix design, preparation of specimens, curing, and compressive strength assessment.

### 3.1 Materials

Ordinary Portland Cement of 53 grade was used as the primary binding material. The cement had a specific gravity of 3.12 and a standard consistency of 32%. Metakaolin, with a specific gravity of 2.40, was used as a supplementary cementitious material, replacing 10% of cement by weight. The fine aggregate used had a specific gravity of 2.46 and a water absorption of 0.1%. Copper slag, obtained as a by-product from the copper industry, had a specific gravity of 3.74 and was used to replace fine aggregate in varying proportions. Coarse aggregate of 20 mm maximum size, having a specific gravity of 2.73 and water absorption of 0.5%, was employed. Polypropylene fibres of 12 mm length were added at a dosage of 0.8% by volume of concrete. To enhance workability, a superplasticizer was added at 1.1% of the weight of cement. Potable water was used for both mixing and curing.

### 3.2 Mix Proportions

The mix proportion for M30 grade concrete was developed in accordance with the guidelines of IS 10262:2019, using a water–cement ratio of 0.40. In the control mix, the quantities of constituents per cubic metre of concrete were 394 kg of cement, 791 kg of fine aggregate, 1068 kg of coarse aggregate, and 157.6 kg of water. In the modified mixes, cement was replaced by 10% metakaolin, polypropylene fibres were added at 0.8%, and copper slag was incorporated as a fine aggregate replacement at 40%, 50%, 60%, and 70%.

**Table -1: Mix Proportion**

Mix ID	Copper Slag%	Metakaolin %	Polypropylene fiber %
CM	0	0	0
40CS10M0.8PPF	40	10	0.8
50CS10M0.8PPF	50	10	0.8
60CS10M0.8PPF	60	10	0.8
70CS10M0.8PPF	70	10	0.8

### 3.3 Casting and Curing of Specimens

For each mix, cube specimens of size 150 × 150 × 150 mm were prepared and cylinder of 150mm x 300mm was also casted. The concrete was placed in moulds in three layers, each compacted using a tamping rod to remove air voids. The specimen were cured in curing tank. Once demoulded, the cubes and cylinder were cured in clean water at room temperature until the respective testing ages of 28 days.



Figure 1 Casting of Concrete



Figure 2 Curing of Cubes and Cylinders

### 3.4 Testing of Concrete

Preliminary tests were conducted on cement, fine aggregate, coarse aggregate, metakaolin, and copper slag to confirm their suitability for use in concrete. These included specific gravity, fineness, consistency, and water absorption tests. The main mechanical property studied was compressive strength and split tensile strength, determined by testing the cube specimens at 28 days using a compression testing machine and split tensile test machine



Figure 3 Compressive Strength Testing



Figure 4 Split Tensile Test

## 4. RESULTS AND DISCUSSION

### 4.1 Compressive Strength at 28 Days

The compressive strength results obtained at 28 days are presented in Table 5.10 and Figure 5.2. The control concrete made with 100% fine aggregate achieved an average strength of 29.83 MPa. With the addition of 10% metakaolin and 0.8% polypropylene fibres, and varying copper slag as a partial replacement of fine aggregate, noticeable improvements were observed. The mix with 40% copper slag recorded 30.66 MPa, which was marginally higher than the control. A significant improvement was seen at 50% copper slag replacement, where the maximum strength of 35.33 MPa was achieved, representing an increase of nearly 18% compared with the control. When the fine aggregate was substituted with 60% copper slag, the compressive strength reduced to 31.0 MPa, which is lower than the optimum mix but still higher than the control. A further increase in replacement to 70% resulted in a strength of 27.0 MPa, indicating a clear reduction below the control mix performance. The results indicate that 50% replacement of fine aggregate with copper slag is the optimum level for compressive strength enhancement. The improvement is mainly due to the denser packing of particles, reduced voids, and additional C-S-H gel formation from the pozzolanic reaction of metakaolin. However, beyond 50% replacement, excessive copper slag leads to reduced bonding and increased free water, resulting in lower strength.

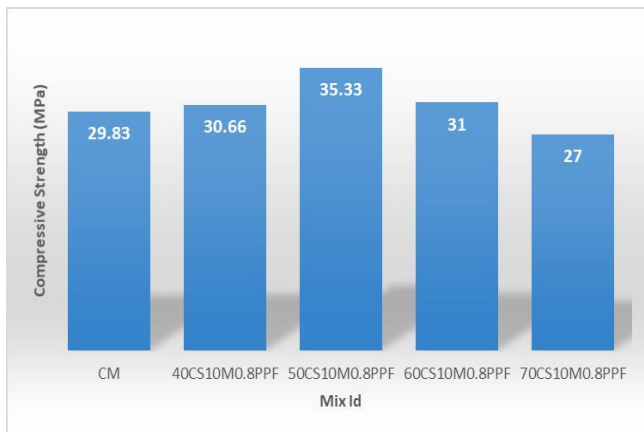


Figure 5 Compressive Strength Variation

#### 4.2 Split Tensile Strength at 28 Days

The split tensile strength values at 28 days are given in Table 5.11 and Figure 5.3. The control concrete showed an average tensile strength of 2.786 N/mm<sup>2</sup>. The incorporation of copper slag improved tensile strength across all replacement levels up to the optimum. At 40% copper slag, the value was 2.90 N/mm<sup>2</sup>. At 50% copper slag, the highest strength of 3.20 N/mm<sup>2</sup> was obtained, which is about 15% higher than the control. The mix with 60% copper slag recorded a split tensile strength of 3.122 N/mm<sup>2</sup>, which, although marginally lower than the optimum value, remained higher than that of the control specimen. When the replacement level was increased to 70%, the strength reduced further to 2.92 N/mm<sup>2</sup>, which was nearly equivalent to the control mix. The improvement in tensile strength can be attributed to the fibre bridging effect of polypropylene fibres, which helps in controlling crack development, and to the improved particle distribution due to copper slag and metakaolin. The decline beyond 50% replacement is related to weaker paste-aggregate bonding and segregation issues.

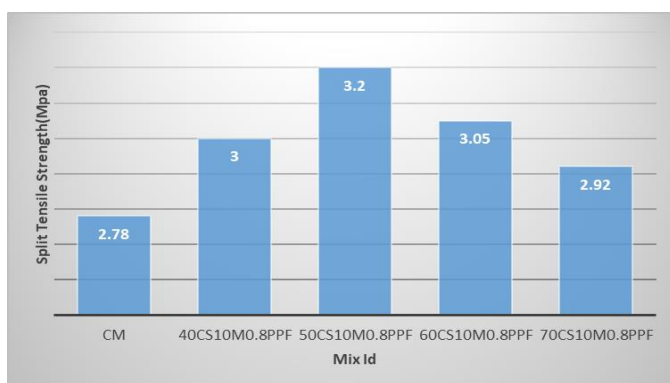


Figure 6 Split Tensile Strength Variation

#### 4.3 Discussion

From the results, it is evident that the use of metakaolin, copper slag, and polypropylene fibres together leads to a

marked improvement in mechanical performance of concrete, with both compressive and tensile strength showing maximum values at 50% copper slag replacement. Metakaolin contributed by enhancing the microstructure through its pozzolanic reaction, copper slag improved the density of the matrix, and polypropylene fibres acted as crack arresters. However, when copper slag exceeded the optimum level, the drawbacks of excess fines and weaker bonding outweighed the benefits, leading to reduced strength. Overall, the combination of 10% metakaolin, 0.8% polypropylene fibres, and 50% copper slag replacement can be considered as the most effective mix proportion for achieving improved strength and durability in M30 concrete.

#### 5. CONCLUSION

The experimental investigation demonstrated that the incorporation of metakaolin, copper slag, and polypropylene fibres significantly influences the strength properties of M30 grade concrete. The results confirmed that the control mix attained a compressive strength of 29.83 MPa at 28 days, whereas the mixes with partial replacement of fine aggregate by copper slag showed noticeable improvements. The optimum compressive strength of 35.33 MPa was achieved at 50 percent copper slag replacement combined with 10 percent metakaolin and 0.8 percent polypropylene fibres, which represents an enhancement of nearly 18 percent over conventional concrete. Beyond this level, further addition of copper slag resulted in reduced strength due to poor bonding and excessive fines in the mix. The split tensile strength followed a similar trend, with the control mix achieving 2.786 N/mm<sup>2</sup> and the optimum mix reaching 3.20 N/mm<sup>2</sup>, indicating an improvement of about 15 percent. The improvement in performance is attributed to the pozzolanic action of metakaolin, which produces additional calcium silicate hydrate, the dense particle packing effect of copper slag, and the fibre bridging mechanism of polypropylene fibres that restricts micro-crack propagation. The findings confirm that the blend of 10 percent metakaolin, 0.8 percent polypropylene fibres, and 50 percent copper slag replacement provides the most effective and sustainable proportion for achieving higher compressive and tensile strength. This study highlights the potential of utilizing industrial by-products such as copper slag and mineral admixtures like metakaolin in combination with synthetic fibres to produce eco-friendly, durable, and structurally efficient concrete suitable for construction applications.

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